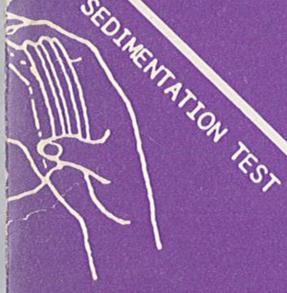
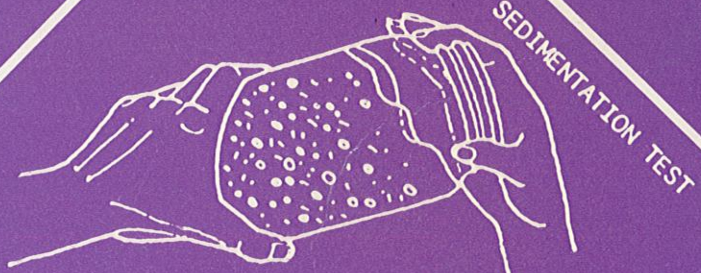
UNCHS (Habitat)

Earth Construction Technology

Manual on Basic Principles of Earth Application





EARTH CONSTRUCTION TECHNOLOGY

MANUAL ON BASIC PRINCIPLES OF EARTH APPLICATION

United Nations Centre for Human Settlements (Habitat)
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FOREWORD

In most rural areas of the developing countries and in some urban low-income settlements, earth is the main material used for shelter construction. Under these circumstances, earth construction is characterized by dilapidated, temporary and unsafe structures. In fact, living examples of good, durable and attractive earth buildings are hard to come by, while the popularity of the material has dwindled to the extent that, even in circumstances where it should be the obvious choice in rural housing construction, preference has been given to relatively modern materials.

In principle, soil is not restricted to low-cost construction, but, rather, forms the basis of a technically sound engineering practice which is comparable to concrete technology or that of any of the popularly adopted building materials. Ultimately, a building material responds to clearly defined functional requirements in the construction process. The merit of earth in construction should be judged by its ability to fulfil a number of construction tasks - notably as a material for walls, floor, renderings and even for roofs. The issue of earth being a low-cost material is incidental and, indeed, an added advantage to these technically viable properties. For this reason, the material should be promoted alongside other conventional materials to the extent that professionals in the construction sector can make a choice for earth in preference over or as an alternative to comparable materials. It is along these lines that the objectives of wide-scale adoption of the material could be achieved while meeting the construction needs of the low-income population.

Following this principle, earth construction faces an obvious disadvantage in comparison with other popularly adopted materials. There is limited knowledge of good earth construction practice. The construction technologies which are predominant in the informal channels for artisan training are defective and inappropriate. In the conventional technical and professional training institutions, there is hardly any coverage of the subject of earth construction apart from basic civil engineering consideration. While architects, town planners, civil engineers, quantity surveyors and numerous sub-professionals in the construction sector have a role to play in promoting the use of earth, the foremost task is to fill a gap in their knowledge, i.e., to provide adequate technical information on earth construction for use by professionals in field implementation projects. It is for this purpose that this set of publications has been provided.

This series of publications on earth construction is made up of four technical manuals, namely, (1) Manual on basic principles of earth application, (2) Manual on production of components, (3) Manual on design and construction techniques, and (4) Manual on surface protection. The four manuals are complementary to each other, yet each is presented in a distinct and concise manner to respond to a specific component of the subject.

These manuals are intended for professionals dealing with projects on earth construction and should serve as useful reference material and aids in actual field practice. This current publication will be supplemented by other publications on various aspects of earth construction for the benefit of a wider group of professionals, programme administrators and policy-makers who are concerned with the subject. Eventually, it is expected that all these efforts will contribute to the provision of detailed and simplified manuals for use by the ultimate field worker - the technician or the craftsman.

The preparation of these manuals is based on an extensive project on earth construction technology undertaken by UNCHS (Habitat) in collaboration with the Government of Belgium. UNCHS (Habitat) is deeply grateful to Messrs. Hugo Houben and Guillaud Hubert, who were the principal consultants for the project.

A. Ramachandran

Dr. Arcot Ramachandran
Under-Secretary-General
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INTRODUCTION

Immense experience has been acquired on building in earth in recent times. It is, however, far from being complete. The criteria for the suitability of a soil currently in use are far from final and should not be too literally interpreted.

The majority of design charts used have been borrowed from road engineering techniques and these are fairly suitable for earth construction. Many suitability criteria, however, were drawn up on a regional scale and are therefore not always universal in application. The best course is to draw on their general approach while adapting them to local conditions. They should be used primarily for their qualitative information.

Interpretation should be as flexible as possible, as should be their amendment, taking into account the ranges of values - which can to some extent be enlarged and still provide good results. Even so, only experienced peronnel who can appreciate the consequences of their use should be allowed to interpret suitability criteria. In stabilization, for example, it is possible to depart to some extent from the ideal conditions described by the suitability criteria, but at the same time the dangers involved in doing so must be appreciated. When a well-defined soil is used regularly, experience and know-how will confirm the accuracy of the values considered (e.g. proportions). It should, however, never be forgotten that the economy of the final product depends basically on choosing a new soil. For large-scale projects, preliminary comparative tests can be carried out on test walls built using different methods and so make it possible to find the most suitable solution. Apart from these, indicator and laboratory (if necessary) tests are essential if the greatest efficiency is to be obtained.

Similarly the suggested suitability criteria must be regarded as a starting point. They cannot be considered as binding recommendations and even less as standards.

I. FUNDAMENTALS OF SOIL SCIENCE

A. Basic properties of soil

1. Texture

Also referred to as the grain size distribution of a soil, texture represents the percentage content of the different grain sizes. This texture of a soil is determined by the sieving of the rougher grains: pebbels, gravel, sands and silts, and by sedimentation for the fine clayey materials. The classification of grain sizes adopted by a large number of laboratories based on the ASTM-AFNOR standards are as follows:

V : Pebbles : 200 mm - 20 mm
V : Gravel : 20 mm - 2 mm
IV : Coarse sand : 2 mm - 0.2 mm
III : Fine sand : 0.2 mm - 0.06 mm
II : Silts : 0.06 mm - 0.02 mm
IIA : Fine silts : 0.02 mm - 0.002 mm
I : Clays : 0.002 mm - 0 mm

It is, moreover, often useful to adopt a simpler classificiation, i.e., the decimal classification.

Pebbles : 200 mm - 20 mm
Cravel : 20 mm - 2 mm
Coarse sand : 2 mm - 0.2 mm
Fine sand : 0.2 mm - 0.02 mm
Silts : 0.02 mm - 0.002 mm
Clays : 0.002 mm - 0 mm

2. Plasticity

Plasticity refers to the property of a soil to submit to deformation without elastic failure characterized by cracking or disintegration. The plasticity of a soil as well as the limits between differing states of consistency are determined by making measurements carried out on the "fine mortar" size of the soil (diameter of grains 0.4 mm). The quantity of water, expressed as a percentage, which corresponds to the limit of the transition between the state of fluid consistency and the state of plastic consistency is called the liquid limit (LL). The transition between plastic and the solid state is called the plast limit (PL). At LL the soil starts to manifest a certain resistance to shearing. At PL the soil stops being plastic and becomes brittle. The plasticity index (PI), equal to LL - Pl, determines the range of plastic behaviour of the soil. The combination of the LL and the PL specifies the sensitivity of the soil to variations in humidity.

3. Compactibility

The compactibility of a soil defines its ability to be compacted to a maximum for a given compacting energy and degree of humidity (optimal moisture content - OMC). When a volume of soil is subjected to the action of a force, the material is compressed and the voids ratio decreases. As the density of a soil is increased its porosity is reduced, and less water can penetrate it. This property is the result of the interpenetration of the grains, which in turn results in a reduction of the disturbance of the structure as the result of water action. The compactibility of a soil is measured by the Proctor compaction test. The compactibility of a soil can be represented on a compactibility diagram such as diagram "C" below, where OMC is plotted against optimal dry density for any given compression energy.

4. Cohesion

The cohesion of a soil is an expression of the capacity of its grains to remain together when a tensile stress is imposed on the adhesive or cementation properties of its coarse mortar (grain size of 2 mm diameter which binds the inert grains together. This property thus contributes to the quantity and adhesive quality of the clays. The coarse mortars may be grouped as follows:

A. Sandy mortar
B. Lean mortar
C. Average mortar
D. Fat mortar
E. Clays

Cohesion is measured by a tensile test in the moist condition sometimes also referred to as the "8" test. Cohesion is plotted in a tensile strength chart "T".

B. Composition of solids in soil

1. Pebbles

Pebbles range in size from 20 mm to 200 mm. They form a rough material which is the result of the disintegration of the parent rock from which they draw their basic characteristics. They may also have beed carried from elsewhere. Young pebbles still have sharp corners. Severely weathered pebbles are rounded as are those which have been carried by watercourses or glaciers.

2. Gravel

Gravel ranges in size from 2 to 20 mm. It is made up of small grains of rough material, which are the result of the disintegration of the parent rock and pebbles. They may also have been carried by water courses and thus be rounded, though angular gravel also exists. Gravel constitutes the skeleton of the soil and imposes a limit to its capillarity and shrinkage.

3. Sands

Sand ranges in size from 0.06 mm to 2 mm. It is often made up of particles of silica or quartz. Some beach sand contains calcium carbonate (shell fragments). The sandy component of a soil is marked by its high internal friction. Sand grains lack cohesion because of the weak effect of films of water close to thier surfaces. The low adsoption of these surfaces limits swell and shrinkage. The open structure and permeability are typical of sand.

4. Salt

The grain size of slit ranges from 0.002 ((2 u) to 0.06mm. From the physical and chemical point of view the silt component is identical to the sand component, the only difference being one of size. Silt gives soil stability by increasing its internal friction. The films of water between the particles grant a certain degree of cohesion to silty soil. Because of their high degree of permeability silty soils are very sensitive to frost. They are subject to small-scale swell and shrinkage.

5. Clays

Clay grains are smaller than 2 u. They differ from other grains in their chemical composition and physical properties. In chemical terms they are hydrated aluminosilicates formed by the leaching process acting on the primary minerals in rock. Physically speaking clays often assume a platy elongated shape. Their specific surface is infinitely greater than that of rougher round or angular particles. Clays are very susceptible to swell and shrink.

6. Colloids

Sandy material is often coated with a sort of gluey paste which sticks it into aggregate. This gluey paste is made up of "colloids", the dimensions of which are less than 2 u. Some of these are the result of the weathering of the parent rock. These are mineral colloids, the chief of which is clay. Clay is not the only mineral colloid. It is often mixed with very fine quartz debris, with hydrated silica, extremely fine crystals of limestone and magnesium colloids, as well as colloidal iron and aluminium oxides. Other colloids result from the decomposition of organic matter. These are the organic colloids: humus and bacterial glues.

C. Soil identification

1. Sampling

(a) Collecting samples

A manual auger or a mechanical version mounted on a lorry can be used. Augers allow rapid sampling to considerable depths. With extensions, depths of between 5 and 6 metres can be reached compared with depths of between 0.60 and 0.70 m without extensions). Normal sizes for augers range from 6 to 25 cm. They weigh about 5 kg, increasing by 3 kg with every 1 m extension. The main drawback of the tool is the risk of mixing surface layers with those at a greater depth.

An alternative is to dig a hole with a side of 1 m to a depth of 2 m. The hole should be properly oriented with respect to the sun in order to facilitate observation. Precautions must be taken to ensure the safety of the labourers, as there is a cave-in risk when working in poorly cohesive material. The excavated earth is removed in its entirety and no samples are taken from it. The soil used in the analysis is taken from one of the sides of the holes by digging sideways into the wall. Samples can also be taken from natural slopes where the dip of the soil layers is clearly visible. Care should be taken to remove all the vegetation and organic matter from the surface.

(b) Sample weight

In principle, 1.5 kg of soil is enough for all basic identification tests, except for compactibility tests, which require 6 to 10 kg. If one brick measuring 29.5 x 14 x 9 cm is to be tested, 10 kg of soil is required. The quantity of soil to be taken for the sample will depend on the number and type of tests to be carried out, on the degree of precision required (as this may make a double test series necessary), on the expenses and difficulties involved (as the cost of a test is often related to the quality of the soil under test), and finally on grain size, as a large-grain soil requires a larger sample than a fine soil.

(c) Sample quality

The sample must be representative of the quality of the soil under test. In order to ensure that the sample is representative, an effort must be made to ensure that the following principles are observed.

- Care must be taken to avoid soil contamination due to the mixing of different sampling horizons;

- Take nothing from and add nothing to the sample. Do not try to improve its natural state;

- Take samples from only a very restricted area;

- If the soil is heterogenous, do not try to take an average but take more samples from each different spot;

- In order to divide a sample up, place it in the shape of a cone on a clean tissue; flatten it and divide it into four. Discard two of the opposing sectors, then shape the material into a cone again and repeat the operation until the desired quantity is obtained.

2. Preliminary tests

Field work requires a number of rapid identification tests to help in determining what soils are likely to be suitable for construction purposes. These simple field tests make it possible to evaluate some of the properties of the material and to determine the suitability of the soil for construction purposes. These tests are somewhat empirical; and they should be repeated to ensure that more than a superficial impression is gained. From these tests it can be seen whether further laboratory testing is justified.

(a) Visual examination

The dry soil is examined with the naked eye to estimate the relative proportions of the sandy and fines fractions. Large stones, gravel, and coarse sand are removed in order to facilitate evaluation (this operation must also be carried out for all the following tests). The fines fraction is made up of grain sizes with a diameter of less than 0.08 mm. This diameter lies at the limit of the resolving power of the human eye.

(b) Smell test

The soil should be smelt immediately after removal. If it smells musty it contains organic matter. This smell will become stronger (if the soil is heated or wetted.

(c) Nibble test

Care should be taken that it is safe to place any samples in the mouth. The tester nibbles a pinch of soil, crushing it lightly between the teeth. The soil is sandy if it grinds between the teeth with a disagreeable sensation. Silty soil can be ground between the teeth but without giving a disagreeable sensation. Clayey soil gives a smooth or floury sensation, and a small piece of it is sticky when applied to the tongue.

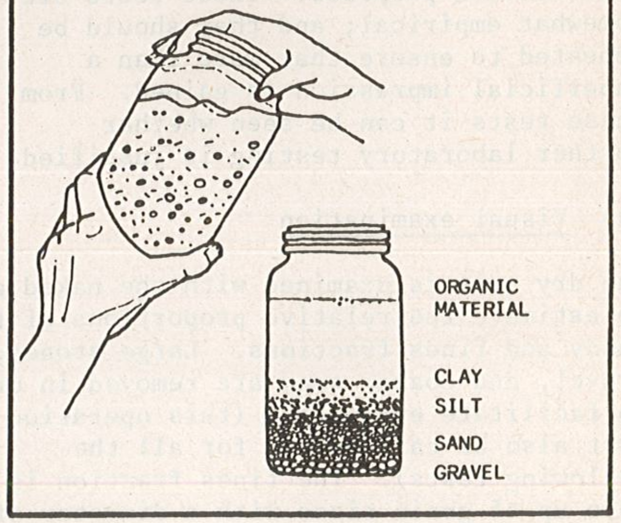
(d) Touch test

After removing the largest grains, crumble the soil by rubbing the sample between the fingers and the palm of the hand. The soil is sandy if a rough sensation is felt and if it has no cohesion when moist. The soil is silty if it gives a slightly rough sensation and is moderately cohesive when moistened. The soil is silty if it gives a slightly rough sensation and is moderately cohesive when moistened. The soil is clayey if when dry it contains lumps or concretions which resist crushing, and if it becomes plastic and sticky when it is moistened.

(e) Sedimentation

The foregoing tests make it possible to form an idea of the texture of the soil and the relative size of the different fractions, as well as of the quality of the fines fraction. To obtain a more exact idea of the soil fractions, a simplified sedimentation test can be carried out in the field. The apparatus required can be simple: a transparent cylindrical glass bottle, with a flat bottom and a capacity of at least one litre and with a neck wide enough to get a hand in, but small enough to be closed off with the palm.

SEDIMENTATION TEST



The test procedure is as follows:

- Fill the bottle a quarter full of soil;

- Fill the remaining three quarters with water;

- Leave the bottle to stand so that the soil is soaked. The soaking can be facilitated by disturbing the soil manually;

- Shake the bottle vigorously;

- Decant the murky water;

- Shake again after an hour and decant again;

- After a further 45 minutes, it will be seen that the sand has been deposited on the bottom of the bottle. Above it is a layer of silt and above the silt a layer of clay. On the surface of the water floats organic debris, while any very fine colloids will remain in suspension in the water. Normally eight hours are allowed to go by before measuring the different layers precipitated. First of all measure the overall depth of the sediment (100 per cent), without including the depth of clear water covering it, and then measure each separate layer.

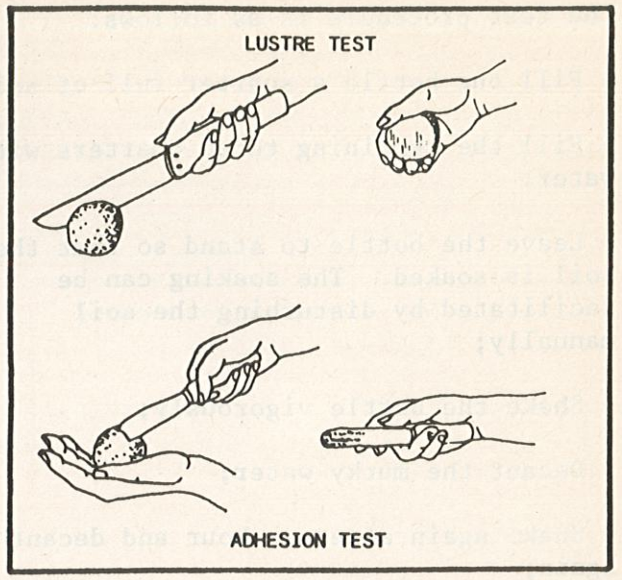
This measurement of the respective depths of the sediment, which makes it possible to estimate the percentage of each grain fraction, is slightly distorted by the fact that the silt and clay fractions will have expanded and are thus slightly larger than they really are.

(f) Lustre test

A slightly moist ball of earth is cut in two with a knife. If the freshly revealed surface is dull, the soil will be predominantly silty. A shiny surface on the other hand indicates the presence of a plastic clayey soil.

(g) Adhesion test

Take a mass of moist soil which does not stick to the fingers and insert a spatula or knife into it. The soil is extremely clayey, if the spatula penetrates it with difficulty, and soil sticks to it upon withdrawal. The soil is moderately clayey, if the spatula can be pushed into it without great difficulty and soil sticks to upon withdrawal. The soil contains only a little clay if the spatula can be pushed into it without encountering any reistance at all, even if the spatula is dirty upon withdrawal.

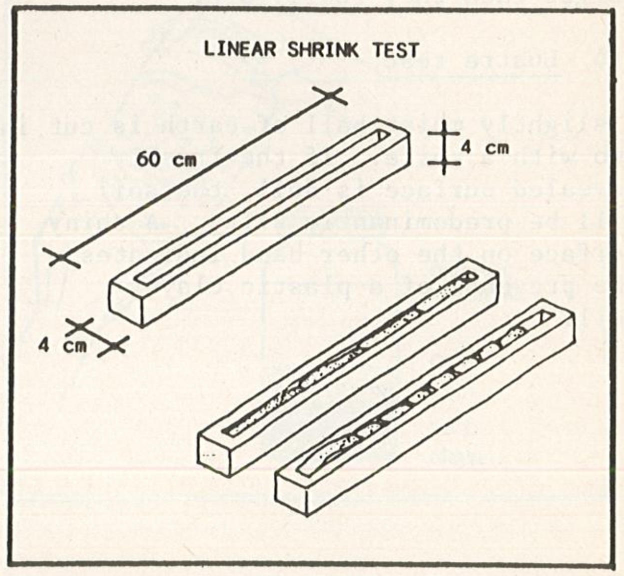


(h) Washing test

Wash the hands with the slightly moistened soil. The soil is sandy if the hands easily rinse clean. The soil is silty if it appears to be powdery and the hands can be rinsed clean without too much difficulty. The soil is clayey if it gives a clayey sensation and the hands can be rinsed clean only with difficulty.

(e) Shrink

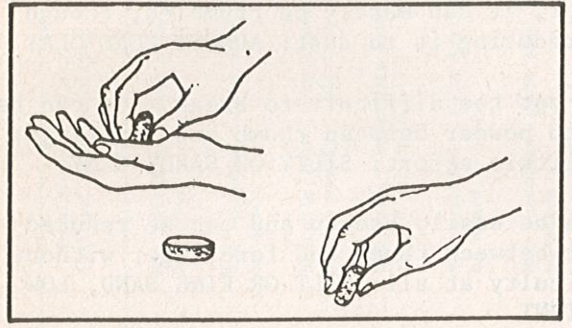
The linear shrink test, or Alcock's test, is performed with the help of a wooden box, 60 cm long, 4 cm wide and 4 cm deept. The inside surfaces of the box are greased before being filled with moist soil with an OMC. The soil is pressed into the corners of the box with a small wooden spatula which is also used to smooth the surface. The filled box is exposed to the sun for a period of three days, or left in the shade for seven days. After this period the hardened and dried mass of soil is pushed to one end of the box and the total shrink of the soil is measured from the soil to the other end of the box.



3. Visual analysis of fines

The analysis appearing below were carried out on the "fine mortar" (diam. 0.4 mm) graded by sieving, or by the decentation test on the grain fraction with a diameter of 2 mm.

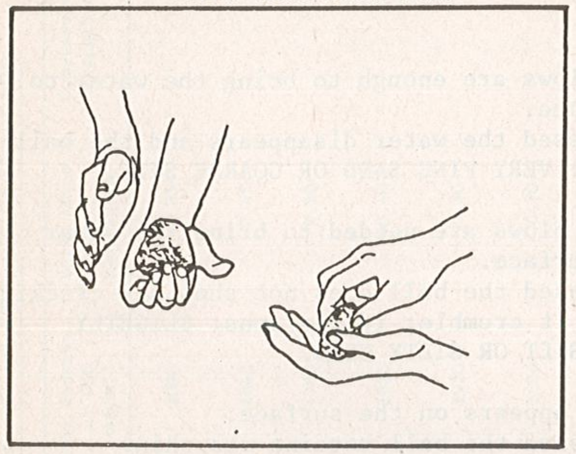
Dry stength test



(a) Dry strength test

- . Prepare two or three pats of soft soil;
- . Place the pats in the sun or in an oven until they have completely dried;
- . Break a soil pat and attempt to pulverize it between thumb and index finger;
- . Estimate the strength of the pat.

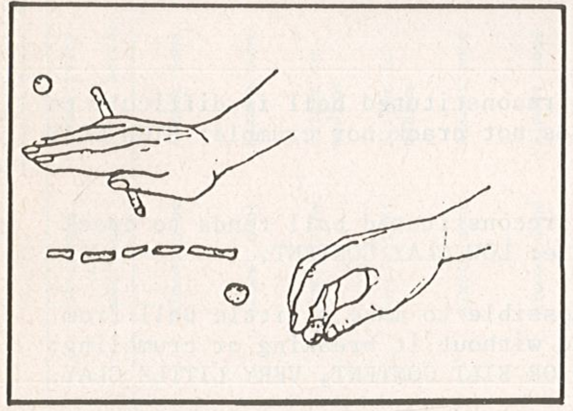
Water retention test



(b) Water retention test

- . Prepare a ball of "fine mortar" 2 or 3 cm in diameter;
- . Moisten the ball so that it sticks together but does not stick to the fingers;
- . Slightly flatten the ball and hold it in the palm of the extended hand. Vigorously hit the palm of the hand holding the ball so that the water runs out. The appearance of the ball may be smooth, shiny or greasy;
- . Next press the ball flat between index finger and thumb and observe the reactions

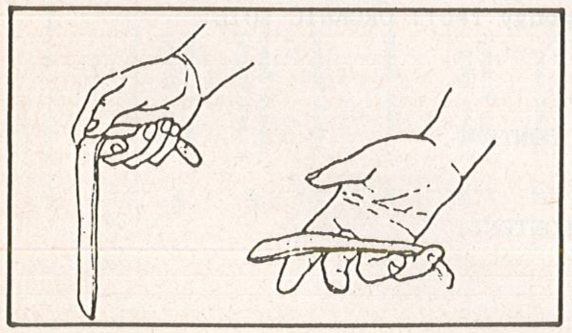
Consistency test



(c) Consistency test

- . Prepare a ball of "fine mortar" 2 or 3 cm in diameter;
- . Moisten the ball so that it can be modelled without being sticky;
- . Roll the ball on a flat clean surface until a thread is slowly formed;
- . If the thread breaks before its diameter is reduced to 3 mm, the soil is too dry; add water;
- . The thread should break when its diameter is 3 mm;
- . When the thread breaks, make it into a small ball again and crush it between thumb and index finger.

Cohesion test



(d) Cohesion test

- . Make a roll of soil about the size of a sausage with a diameter of 12 mm;
- . The soil should not be sticky and should be capable of being shaped so that it makes a continuous thread 3 mm in diameter;
- . Place the thread in the palm of the hand. Starting at one end carefully flatten it between index finger and thumb to form a ribbon of between 3 and 6 mm in width as long as possible;
- . Measure the length obtained before the ribbon breaks.

OBSERVATIONS	INTERPRETATIONS
Dry strength test:	
High dry strength	A dry pat is very difficult to break. When it does, it breaks with a snap, like a dry biscuit. The soil cannot be crushed between thumb and forefinger, it can merely be crumbled, though without reducing it to dust: ALMOST PURE CLAY.
Moderate dry strength	A pat is not too difficult to break. It can be crushed to powder between thumb and forefinger after a little effort: SILTY OR SANDY CLAY.
Low dry strength	A pat can be easily broken and can be reduced to powder between thumb and forefinger without any difficulty at all: SILT OR FINE SAND, LOW CLAY CONTENT.
Water retention test:	
Rapid reaction	5 or 6 blows are enough to bring the water to the surface. When pressed the water disappears and the ball crumbles: VERY FINE SAND OR COARSE SILT.
Slow reaction	20 to 30 blows are needed to bring the water to the surface. When pressed the ball does not show any cracking nor does it crumble; it flattens: SLIGHTLY PLASTIC SILT OR SILTY CLAY.
Very slow reaction or no reaction at all	No water appears on the surface. When pressed the ball retains its shiny appearance: CLAYEY SOIL.
Consistency test:	
Hard thread	The small reconstituted ball is difficult to crush, does not crack nor crumble: HIGH CLAY CONTENT.
Medium hard thread	The small reconstituted ball tends to crack and crumble: LOW CLAY CONTENT.
Fragile thread	It is impossible to make a little ball from the thread without it breaking or crumbling: HIGH SAND OR SILT CONTENT, VERY LITTLE CLAY.
Soft or spongy thread	The thread and the reconstituted ball has a soft or spongy feel: ORGANIC SOIL.
Cohesion test:	
Long ribbon (25 to 30 cm)	HIGH CLAY CONTENT.
Short ribbon (5 to 10 cm obtained with difficulty)	LOW CLAY CONTENT.
No ribbon at all	VERY LOW CLAY CONTENT.

D. Suitability of soils for stabilization

	Soil	Shrinkage and swelling	Sensitivity to frost action	Bulk density at OMC (kg/m')	Voids ratio (vs = 2700 kg/cm')	Compressive strength dry	General suitability (without stabilization)
GW	Clean gravel Well graded	Almost none	Almost none	2000	0.35		Not suitable. Fine soil should be added.
GP	Clean gravel Poorly graded	Almost none	Almost none	1840	0.45		Not suitable. Fine soil should be added
GM	Silty gravel	Almost none	Slight to medium	1760	0.50		Suitable, but lacks cohesion. Erodes easily. Add fine soil.
GC	Clayey gravel	Very slight	Slight to medium	1920	0.40		Suitable. Sometimes fine soils should be added.
SW	Clean sand Well graded	Almost none	Almost none	1920	0.40		Not suitable. Fine soil should be added.
SP	Clean sand Poorly graded	Almost none	Almost none	1600	0.70		Not suitable. Fine soil should be added.
SM	Silty sand	Almost none	Slight to high	1600	0.70		Suitable, but lacks cohesion. Erodes easily. Add fine soil.
SC	Clayey sand	Slight to medium	Slight to high	1700	0.60		Suitable. Sometimes fine soils should be added.
CL	Low-plasticity clay	Medium to high	Slight to high	1520	0.80	Slight to high	Sometimes suitable. Sandy soil should be added.
ML	Low-plasticity	Slight to high	Medium to very high	1600	0.70	Very slight	Suitable, but lacks eventual cohesion.
OL	Organic silt and clays with low plasticity	Medium to high	Medium to high	1440	0.90		Not suitable. Sometimes acceptable.
CH	Highly plastic clay	High	Very slight	1440	0.90	Medium to very high	Rarely suitable. Sandy soil should be added.
MH	Highly plastic silt	High	Medium to high	1600	0.70	Very slight to medium	Very rarely suitable.
OH	Highly plastic organic	High	Very high	1600	0.70	Medium to high	Not suitable.
Pt	Peat and other highly	Very high	Slight				Suitable as sod.

II. PRINCIPLES OF SOIL STABILIZATION

A. Basic considerations

1. Fundamental problem

Building in soil implies a choice between three main approaches:

- Using the soil available on the site and adapting the project as far as possible to the quality of the soil;

- Using another soil more suited to the requirements of the project but which has to be brought to the site;

- Modifying the local soil so that it is better suited to the requirements of the project.

The third possibility is generally referred to as "soil stabilization" and comprises the entirety of techniques permitting the improvement of the properties of the soil.

2. Definition

Stabilizing a soil implies the modification of the properties of a soil-water-air system in order to obtain lasting properties which are compatible with a particular application. Stabilization is nevertheless a complex problem, as an extremely large number of parameters are involved. In fact a knowledge of the following is necessary:

- The properties of the soil requiring stabilization;

- The planned improvements;

- Project economy: costs and delays involved in soil stabilization;

- The soil construction techniques chosen for the project and the system of construction;

- Maintenance of the completed project; maintenance cost.

The improvement of the properties of the soil by stabilization will be successful if the procedure used is compatible with the imperatives of the programme - in particular the cost of and delays in construction, and the cost of maintenance.

3. Objectives

Action can be directed at only two characteristics of the soil itself, i.e. its texture and structure. There are three courses of action:

- Reducing the volume of interstitial voids: acts on porosity;

- Filling the voids which cannot be eliminated: acts on permeability;

- Improvement of the bonding between grains; acts on mechanical strength.

The main objects aimed at are:

- Achieving better mechanical characteristics: improving dry and wet compressive strength; tensile strength and sharing strength;

- Achieving better cohesion;

- Reducing porosity and changes in volume: shrink and swell due to water;

- Improvement of resistance to wind and rain erosion: reduction of surface abrasion and water-proofing.

4. Procedures

There are three basic stabilization procedures:

(a) Mechanical stabilization: this is the compaction of the soil resulting in changes in its density, mechanical strength, compressibility, permeability and porosity.

(b) Physical stabilization: here the properties of the soil can be modified by acting on its texture: e.g., the controlled mixing of different grain fractions. Other techniques can involve heat treatment, drying or freezing, electrical treatment, electro-osmosis to improve the draining qualities of the soil, and giving new structural qualities.

(c) Chemical stabilization: In this procedure other materials or chemicals are added to the soil, thus modifying its properties either by a physico-chemical reaction between the grains and the materials or the added product, or by creating a matrix which binds or coats the grains. A physico-chemical reaction can lead to the formation of a new material: for example a pozzolan resulting from a reaction between clay and lime.

5. When is stabilization required

Stabilization is not compulsory. It can be ignored quite satisfactorily and the soil can be used for construction without stabilizing.

Nevertheless, there is clearly a tendency at present to the over use of stabilization, which is regarded as a universal panacea for all problems. This attitude is unfortunate as stabilization can involve considerable extra costs, ranging from 30 to 50 per cent of the final cost of the materials. Furthermore stabilization complicates the production of the material, e.g., through longer preliminary studies of the behaviour of the material.

It is thus advisable to insist that stabilization be used only when absolutely essential and that it should be avoided where economic resources are limited.

- Do not stabilize when the material is not exposed to water: (i.e., sheltered walls, dressed walls, inside walls, architecture designed to accommodate the exigencies of soil as a building material).

- Stabilize when the material is very exposed: (i.e., when there is poorly designed architecture which ignores the rules of building with earth; or requirements imposed by the site, such as a damp site, walls exposed to driving rain, and so on. However, there may be other reasons for stabilizing the material such as:

- The improvement of the soil's compressive strength;

- Raising the material's bulk density, or even reducing it.

B. Methods of stabilization

1. Densification

There are two different ways in which density can be increased:

(a) Either by mechanically manipulating the soil, so that a maximum of air can be eliminated; by kneading and compressing the soil. Grain size distribution is not affected, but grain structure is changed because the grains are redistributed. The soil is not simply compressed in its original state. It is first ground to make it more uniform, and then compressed. After the grinding phase, it is possible - but not indispensable - to make use of dispersants or waxes which may facilitate compaction.

(b) By filling the voids as far as possible with other grains. If this second method is to be used, grain size distribution must be perfect: the voids left between each group of grains is filled by another group of grains. This method acts directly on grain size distribution.

2. Reinforcement

If there are reasons for not acting on the grain size distribution of the soil and if the material remains overly sensitive to movements induced by various causes such as compression, tension, water action and thermal expansion, among others, these movements can be counteracted with an armature. This armature can be made of a wide variety of fibres: animal, vegetable, mineral or synthetic. The fibre armature has its effect at the macroscopic level, that is to say at the level of grain aggregations rather than at the level of the individual grains.

3. Construction

A three-dimensional matrix can be introduced in the soil. Strong and inert, it resists all movements of the soil. This is in essence the consolidating action of cementing. It results in the filling of the voids with an insoluble binder which coats the grains and holds them in an inert matrix. The main stabilizer which acts by this mechanism is Portland cement. Similar results can be achieved with electrolytic solutions of sodium silicate salts or with certain resins and adhesives. Viewed as a chemical reaction, the essential characteristic of this stabilization mechanism is that the formation of the inert matrix is relatively independent of the clay. In fact, the main consolidating reactions take place in the stabilizer itself and between the stabilizer and the sandy fraction of the soil. Even so, secondary reaction between the stabilizer and the clayey fraction may be observed. The quantity and quality of the clay has an effect on the efficiency of the stabilization procedure and may alter the mechanical behaviour of the material.

4. Linkage

In this case the inert matrix introduced in the soil includes the clays. Two mechanisms are known and they give the same result.

(a) An inert matrix is created by the clays: use is made of the negative and positive charges of the clay plates or their chemical composition to bind them together by means of a stabilizer, which plays the role of binder or catalyst for this bond. Certain chemical stabilizers act in this way, including certain acids, polymers, flocculants, etc.

(b) An inert matrix is formed by the clay. A stabilizer reacts with the clay and precipitates a new inert and insoluble material, which is a sort of cement. This is the pozzolan reaction and is obtained primarily with lime. The reaction proceeds slowly and depends essentially on the quantity and quality of the clay.

5. Imperviousness

This stabilization method helps to reduce water erosion, swell, and shrinkage when the material is subjected to successive wetting and drying cycles. There are two possible waterproofing methods:

(a) All the voids, pores, cracks and microcracks are filled with a material which is unaffected by water. Bitumen is one of the best examples of a product which acts in this way. This stabilization method is particularly suitable for sandy soils with a good stability for their volume and which are not much affected by the movement of water. It is equally suitable for silty and clayey soils which need larger amounts of stabilizer because of their greater specific surface.

(b) A material is dispersed in the soil which expands upon the slightest contact with water and prevents the infiltration of pores. A typical material of this type is bentonite.

6. Waterproofing

Here the object of the procedure is the movement of water and water vapour in the soil. This can be achieved either by changing the nature of this water, or by reducing the sensitivity of the clay plates to water.

Three systems are used:

(a) The modification of the state of the pore water: drying the soil by introducing calcium chloride into it. This raises surface tension, reduces the vapour pressure of the water and the evaporation rate, and also reduces variation in moisture content.

(b) Ion exchange: ions are replaced by others until the ions are very well fixed to the clay plates and the water can no longer dilute them. Certain acids can give rise to this phenomenon.

(c) Molecules are fixed on one of the extremities of the clay plates on the outside of compact aggregates. The other ends of these molecules are water repellent. Certain quaternary amines and resins work in this way.

C. Suitability of soils for stabilization

1. Soils suitable for fibres and mineral aggregates

These criteria for fibre -stabilized or mineral-stabilized soils are accompanied by the maximum compression rates to which the materials may be subjected and at which they can be used in all safety. It may thus be observed that fibre-stabilized soils should not be worked with at above 3 daN/cm^2 and that mineral-stabilized soils have a limit of 5 daN/cm^2. These are the maximum compression rates. Certain soils may not be able to achieve these rates. Thus the values given by the performance curve should not be interpreted as permissible values but as values which should in no case be exceeded.

Usage criteria applicable to soil stabilized with fibre and minerals exist. These were drawn up in the 1940s as the result of prolonged laboratory research on a very large number of samples. These laboratory observations were subsequently enriched by a mass of practical construction experience. Since then these criteria have been successfully applied to thousands of projects. Nevertheless, these criteria were established in northern Europe, and are above all applicable to the soils of that region, which are of a loess-based silt sort. It is possible that these criteria can be adopted to other soil types, but only after extensive verification.

2. Soils suitable for cement

Nearly all soils, except those which have an excessive content of organic material, can be treated with cement and thus undergo a drastic improvement in their properties. Salt-rich soils are also difficult to stabilize with cement; even so, an increase in the proportion of cement can often bring good results. Soils which have a large clay fraction mix only with difficulty and require large quantities of cement. When the mixing process is very closely controlled under laboratory conditions good results can be achieved with clayey soils. In practice, however, cement is not used for stabilizing clay when the liquid limit is higher than 30 per cent. Preliminary treatment of these extremely clayey soils with hydrated lime may improve the likelihood of obtaining good results with cement added at later date. Numerous tests give indications regarding the suitability and proportion of cement.

- Abrasion test: the proportion of cement should reduce loose material to 3 per cent after 50 cycles, which is an excellent performance.

- Erosion test: the proportion of cement should reduce the mean depth of holes to 15 mm - an excellent performance for this extermely severe test.

- Wetting-drying: an optimum proportion should reduce material losses to 10 per cent - an excellent performance for this extremely severe test.

- Freeze-thaw: an optimum proportion should reduce material losses to 10 per cent: an excellent performance for this excessively severe test.

- Shrink (based on the Alcock test):

Linear shrink (mm)	Cement: soil (vol.)
Less than 15	1 : 18
From 15 to 30	1 : 16
From 30 to 45	1 : 14
From 45 to 60	1 : 12

These values are applicable to soils compressed to a maximum of 40 dAN/cm^2. The quantity of cement can be reduced to less than 30 per cent for soils compressed to 100 daN/cm^2.

- Organic matter:

When the pH is greater than 7 (alkaline or basic): calcareous soils, brown alkaline soils, and some gley soils can be stabilized with 10 per cent cement: rates of between 1 and 2 per cent of organic matter are in general not a problem.

When the pH is less than 7 (acid): gley soils can be successfully stabilized with 10 per cent cement if the content of organic matter is less than 1 per cent. Podsols and acidic brown soils can sometimes be stabilized with success if they contain less than 1 per cent of organic matter. If anomalies are found to exist, preliminary treatment with calcium chloride (1 to 2 per cent) may bring about a certain improvement.

3. Soils suitable for lime

Lime has only a very limited effect on soils with a high organic matter content (content higher than 20 per cent) and on soils short of clay. It is more effective and can be more effective than cement on clay-sand soils and especially on very clayey soils. The effects of lime are thus highly dependent on the nature of the soils involved, but a comparison with the effects of cement can, in many cases, be attempted. It has been observed that lime reacts far more quickly with montmorilllonite clays than with the kaolinites, reducing the plasticity of the montmorillonites and having only a slight effect on the plasticity of the kaolinites. Water content has a significant effect on clay soils which can be stabilized with lime, particularly in the pulverization and compaction stage. Natural pozzolans react particularly well with lime.

For the rest it may be noted that the proportions of lime quoted are for industrial quality lime containing between 90 and 99 per cent of quick lime. For lime produced by less sophisticated methods, which may contain only 60 per cent of quick lime (the rest being made up of unfired or over-fired components), the proportion must be increased. The two main methods of improving the performance of soil with lime may be summarized as follows:

(a) Modification of the soil: the lime is added until a setting point is reached. This operation reduces the plasticity of the soil and improves its flocculation.

(b) Soil stability: the proportions are much higher. Reference monographs on the suitability of soils and the proportion of lime must be interpreted with a great deal of reserve.

Tests should be carried out only after allowing a curing period of three months.

- Abrasion test: the proportion of lime should reduce material lost to 3 per cent after 50 cycles - an excellent performance.

- Erosion test: the proportion of lime should reduce the mean depth of holes to 15 mm - an excellent performance for this extremely severe test.

- Wetting-drying: the proportion should reduce material losses to 10 per cent - an excellent performance for this extremely severe test.

- Freeze-thaw: the proportion of lime should reduce material losses to 10 per cent: an excellent performance for this excessively severe test.

- Comprehession strength: the reactivity of soils containing lime was determined by Thompson in 1964. The soils are stabilized with the optimal proportion of lime; the increase in compression strength after curing for seven days at 23°C is defined as the reactivity of the soil with the lime:

Group	Increase	Reactivity
1	1	Non-reactive
2	1 to 3.5	Non-reactive
3	3.5 to 7	Reactive
4	7 to 10.5	Reactive
5	10.5 and more	Reactive

This makes it possible to decide quickly if further testing is justified.

4. Soils suitable for bitumen

Although clayey soils have been successfully treated with cut back or hydrocarbon emulsions, stabilization with hydrocarbons is more suitable for sandy soils or sandy-gravel soils, for soils lacking in cohesion or when an impermeable finish is particularly desired. With extremely clean sandy soils, the low adhesion of the bitumen to the surface of the silicaceous particles can lead to the separation of the bitumen under the action of water, with the result that the stabilizing effect of the bitumen on the soil is considerably reduced. Moist soils are in general not suitable for bitumen stabilization, because of the difficulty of mixing the hydrocarbon with the soil.

- Soluble salts: their presence in a soil is likely to lead to the deterioration of the soil as a result of the successive hydration and dehydration of the soil. Salts also have a tendency to cause efflorescence. Furthermore, in the presence of a stabilizer such as bitumen, they can be very harmful to the binding films between the bitumen and the clays. The presence of salts in a soil which can be stabilized with a bitumen should preferably not exceed 0.25 per cent.

- Proportioning: the IIHT (California, United States) makes recommendations for adobe which involves carrying out tests by progressively increasing the bitumen content as follows (in percentage terms):

Cutback : 2, 3, 4, 5
Emulsion : 3, 4, 5, 6

Each test is carried out on three or four samples which are tested for compression and bending strength, and for erosion resistance until satisfactory results are obtained. IIHT also points out that excessively clayey soils requiring more than 3 per cent of cutback or 6 per cent of emulsion are not suitable for making adobes because of their marked shrinkage.

For emulsions the following figures may be given:

High sand content soils: 4 to 6 per cent
Low sand content soils : 7 to 12 per cent
Clayey soils : 13 to 20 per cent

The percentage is for the hydrocarbon itself and not for the suspending liquid.

III. CHARACTERISTICS OF SOIL STABILIZERS

A. Fibre

Stabilization by means of fibre reinforcement, very often straw, is widely used. Straw should, in fact, be regarded as a structural reinforcement agent, similar to gravel. Nowdays, even in the most modern and industrial settings, such as in adobe production in the United States of America, straw combined with bitumen is often added to the soil. This method of stabilization is interesting because it can be adapted to various methods of execution, with soil used in the liquid or plastic state, or even with compaction techniques. Fibres are mainly employed for making kneaded blocks with largely clayey soils, which usually suffer a considerable measure of shrinkage. Craft production of straw-stabilized adobe brick varies greatly, and quite apart from this straw is also used for daub, clay-straw, cob, as well as compressed blocks and rammed earth.

Fibres hinder cracking upon drying by distributing the tension arising from the shrinkage of the clay throughout the bulk of the material. They accelerate drying because they improve the drainage of moisture towards the outer surface through the channels afforded by them. On the other hand, fibres increase absorption in the presence of water. They lighten the material. The volume of straw is often very large, reducing the bulk density and improving its insulating properties. Fibres increase tensile strength. This is undoubtedly their most interesting property.

Earth materials reinforced with fibres can stand up very well to cracking and resist crack propagation. Considered at the level of a potential crack, the fibre opposes the formation of crack in step with the increase in the stress. The degree of shear strength depends largely on the tensile strength of the fibres. Apart from this, good compressive strength can also be achieved with fibre reinforcement, which depends both on the quantity of fibre used and on the initial compressive strength of the soil, the initial tensile strength of the fibres and the internal friction between the fibres and the soil. Some research seems to suggest that preliminary rotting of the straw in the soil for a period of several weeks produces lactic acid which has a secondary effect on the efficiency of the stabilizing action.

With respect to dry compressive strength, the addition of such fibres as straw permits an increase in strength of at least 15 per cent in relation to the material without fibres. In very exceptional cases, the fibres will make hardly any difference at all to the compressive strength, as for example is the case with very sandy material. Fibre-stabilized blocks can withstand high stresses as they absorb a fairly high amount of applied energy. This makes their use particularly attractive in earthquake-prone regions. The addition of fibres makes a fundamental difference to the behaviour of the bricks beyond the failure point. Where non-reinforced materials crack into bits, reinforced blocks stay in one piece and will continue to increase in compressive strength beyond the failure point of non-reinforced blocks.

The strength of reinforced blocks depends on the quantity of the fibres added, but there is an optimum quantity which should not be exceeded. This is because an overly large quantity reduces density too much, while the number of contact points between the fibre and soil, which are responsible for transmitting stress, becomes too low and the strength of the block is reduced. The minimum proportion for satisfactory results starts at 4 per cent by volume. Quantities of between 20 and 30 kg per m^3 are very common. The straw should by preference be chopped into stalks between 4 and 6 cm long. The best results are obtained when the stalks are scattered in all direction in the soil. Excessively long stalks, in parallel, do not yield good results. Nor are good results obtained when fibres are concentrated in specific spots, or in nests - which may happen when too much fibre is used.

Fibres can also be used together with other stabilizers such as cement, lime, and bitumen. If straw is used with bitumen, the bitumen must be first added to the soil and thoroughly mixed before adding the straw. If the operations are carried out in a different sequence there is a danger that the straw and the bitumen will conglomerate independently of the soil.

The fibres contained in the soil will be preserved without deterioration on condition that the material is kept dry. If the material remains in a moist environment for too long, there is a danger that the fibres will rot. An alternating wetting and drying cycle will not encourage rotting as long as proper drying is certain. Analysis of very ancient material (e.g., adobe from the Eghpt of the Pharaohs) has clearly demonstrated this. Fibres may also be attacked by rodents and harmful insects, such as termites, particularly when wet.

The main types of fibers are:

(a) Plant fibres: straw of all kinds: barley, rye, hard and soft wheat, winter barley, lavender. Chaff of cereal crops: wheat, rice, barley, etc. Light fillers such as sawdust and shavings. Other suitable vegetable fibres include hay, hemp, millet, cane trash, coir fibres, sisal, manila, elephant grass, and fibres of bamboo, palm and hibiscus, as well as the left-overs after scutching hemp and flax.

(b) Animal fibres: fur and hair from livestock.

(c) Synthetic fibres: colophane, steel, and glass wool/fibres.

B. Cement

Hydrated cement reacts in two different ways in soil:

- It may react with itself or with the sandy skeleton. This results respectively in the formation of a pure hydrated cement mortar, or the formation of a conventional mortar.

- It may undergo a three-phase reaction with the clay:

(a) Hydration sets off the formation of cement gels on the surface of the clay aggregations. The lime which comes free during the hydration of the cement tends to react with the clay. The lime is quickly used up and the clay starts to degenerate;

(b) Hydration proceeds and encourages the disaggregation of the clay aggregates. The latter are deeply penetrated by the cement gels;

(c) The cement gels and the clay aggregates become intimately entwined. Hydration continues but more slowly.

In fact three mixed structures are obtained:

- An inert sandy matrix bound with cement;

- A matrix of stabilized clay;

- A matrix of unstabilized soil.

Stabilization does not affect all the aggregate. A stabilized matrix covers the composite aggregations of sand and clay.

The greatest effect is obtained by compression in the moist state. In the plastic state 50 per cent more cement is required to achieve the same effect. The greatest compressive strength is obtained with gravels and sands rather than with silts or clay. For soil, the required quantities of cement depend on its grain size distribution and structure, and the way that it is used. Good results can be obtained with between 6 and 12 per cent. Some soils require only 3 per cent, while the same proportion in others behaves less well than if no cement at all had been used. Generally speaking at least 6 per cent of cement is required in order to obtain satisfactory results. The compressive strength remains highly dependent on the quantity of cement used. In comparable local conditions and for the same wall thickness (15 cm), a stabilized earth brick will not necessarily be more economical than a concrete block. A preliminary study of the comparative costs is recommended.

Ordinary Portland cement or cements of the same class are very suitable. There is no point in using high-strength cements, as these produce no particular improvement and are moreover very expensive. High-strength cements spoil very easily, making them unsuitable for use on work sites far from the factory. Preference should therefore go to Portland cements of the classes 250 or 350. Cements containing other materials such as slags, fly ash and pozzolans can also be used, although these cements will only be available close to steel plants and power stations, and similar localities. In contrast, cements with high contents of other materials should not be used because of their sensitivity when curing. These include iron Portland cement, blast-furnace cement, mixed metallurgical cements and slag clinker cements.

Certain products, added in small quantities to the soil cement during mixing, may improve the characteristics of the finished product.

(a) Some organic products (amine acetate, melamine, aniline) and certain inorganic products (ferrous chloride) reduce the sensitivity of some soils to water.

(b) Lime (2 per cent) can reduce the harmful effects of organic matter, as does calcium chloride (0.3 to 2 per cent), which also speeds setting. The lime also serves to modify the plasticity of the soil and to limit the formation of nodules.

(c) Soda-based additives increase the reactivity of the soil and can induce cementation reactions supplementary to that of the cement with the soil particles. NaOH (sodium hydroxide) can be added in a proportion of 20 to 40 g per litre of the mixing water, while between 0.5 and 1.1 per cent of $NaSO_4$ can be added, or 1 per cent of Na_2CO_3; or 1 per cent Na_2SiO_2.

(d) Between 2 and 4 per cent of bitumen added as emulsion or cut-back makes the soil-cement waterproof.

Production procedures

(a) Crushing

Good cement stabilization demands thorough mixing of the components. The fine elements must not be allowed to form nodules with a size of more than 10 mm. The presence of 50 per cent nodules 5 mm can cut compressive strength by half.

(b) Mixing

Good distribution of the cement and the uniformity of the material is provided by mixing. It is important to have a dry soil if the best mixing conditions are to be attained. In wet climates this may make preliminary drying of the soil necessary. Grinding may accelerate drying and help to break up lumps. The water required for the mix should only be added at the very end of the mixing process, after the very necessary dry mixing phase.

(c) Moulding

The material should be compacted immediately after mixing, before the cement starts to set, and with a controlled moisture content which will be close to OMC. A 4-per cent difference in water content, either more or less, can mean a significant difference in the quality of the material. As a general rule, soil with a high clay content ought to be compacted slightly moister than OMC, while sandy soils should be compacted slightly drier than OMC.

(d) Drying

The strength of a soil cement increases with age. A minimum curing period of 14 days is absolutely essential, although 28 days is better. During this period the material should be kept in a moist environment, sheltered from the sun and protected from the wind, in order to prevent excessively rapid surface drying, which may cause shrink cracking. The materials should be allowed to dry when compacted, and moistened by spraying or covered with a plastic sheet, which allows temperatures to rise and gives an RH close to 100 per cent. The longer this moist-drying cure is allowed to go on, the greater will be the strength of the material.

C. Lime

The theory of lime stabilization suggests five basic mechanisms.

(a) Water absorption: Quicklime undergoes a hydration reaction in the presence of water or in moist soil. This reaction is strongly exothermic with the release of about 300 kcal for every kg of quicklime.

(b) Cation exchange: When lime is added to a moistened soil the latter is flooded with calcium ions. Cation exchange then takes place, with calcium ions being replaced by exchangeable cations in the soil compounds, such as magnesium, sodium, pottasium and hydrogen. The volume of this exchange depends on the quantity of exchangeable cations present in the overall cation exchange capacity of the soil.

(c) Flocculation and accretion: As a result of the cationic exchange and the increase in the quantity of electrolytes in the pore water, the soil grains flocculate and tend to accrete. The size of the accretions in the fine fraction increases. Both grain size distribution and structure are altered.

(d) Carbonation: The lime added to the soil reacts with carbon dioxide from the air to form weak carbonated cements. This reaction uses part of the lime available for pozzolanic reactions.

(e) Pozzolanic reaction: This is by far the most important reaction involved in lime stabilization. The strength of the material results largely from the dissolution of clay minerals in an alkaline environment produced by the lime and the recombination of the silica and alumina in the clays with the calcium to form complex aluminium and calcium silicates, thus cementing the grains together. The lime must be added to the soil in sufficient quantities in order to proceed and maintain a high pH, which is necessary for the disolution of the clay minerals for long enough to allow an effective stabilization reaction.

1. Effectiveness and proportions

When 1 per cent of quicklime is added to the soil the exothermic hydration reaction dries the soil, removing between 0.5 and 1 per cent of water. The addition of 2 to 3 per cent of quicklime immediately provokes a reduction of the plasticity of the soil and the breaking of lumps. This reaction is called the fixing point of the lime. For ordinary stabilization work between 6 and 12 per cent is used, similar to the amounts required for cement stabilization - the difference being that with lime there is an optimum quantity for each soil.

Sophisticated industrial procedures make use of high pressures and steam treatment in an autoclave with the proportion of lime rising to as much as 20 per cent. The products obtained are similar to those obtained in the silica-lime industry. Lime stabilization is particularly well suited to pressure moulding procedures.

2. Types of lime

(a) Non-hydraulic limes are produced by burning very pure limestones. They represent the main source of lime for use in stabilization.

- Quicklime (CaO): Quicklime is produced directly by burning the stone in kilns. The delicate conditions of storage and maintenance required can limit its use. Quicklime is extremely hygrospcopic (i.e., it attracts water) and must be protected from moisture. It is a caustic material and must be handled with great care. It becomes very hot in the hydration stage (up to 150°C). Weight-for-weight it is more effective than slaked lime, because it can supply greater quantities of calcium ions. In moist soils it can absorb the water required for its hydration.

- Slaked lime $(CaOH)_2$: Slaked lime is obtained by hydrating quicklime. Widely used for stabilization, it does not have the drawbacks of quicklime. Fat slaked limes do not have to be very finely crushed to be effective. Industrial qualities contain between 90 and 99 per cent of "active lime" while craft-produced lime may only contain between 70 and 75 per cent, with the rest being unburnt or excessively burnt materials. The proportions used for stabilization must be adapted in consequence.

(b) Hydraulic lime is similar to cement. Its use should not be considered unless other qualities of lime are not available. Natural hydraulic (XHN) limes are more effective stabilizers than artificial hydraulic limes.

(c) Agricultural limes are used to improve agricultural soils and usually have no stabilizing effect at all.

Additives

Some additives mixed with limes in small quantities can have special effects.

(a) To increase the reactivity of the soil:

. Caustic soda;
. Sodium sulphate;
. Metasilicate of sodium;
. Carbonate sodium;
. Sodium aluminate.

The quantity used varies from 1/4 to 2 molecular grams per litre of the water used for compaction.

(b) To increase compressive strength:

. Portland cement is added in quantities of up to 100 per cent of the lime.

(c) To increase the effectiveness of stabilization for sandy silt soils and reduce the swell due to the slaked lime:

. Magnesium sulphate is added at a rate of about 1/4 of the weight of the lime.

(d) To make the soil waterproof:

. Potassium sulphate;
. Bitumen products;
. Other water repellents.

3. Production procedure

(a) Crushing

This operation is important and must be carried out with the greatest care. The more finely the clay is crushed, the more active the lime will be in attacking the clay. The operation may be difficult because clay is highly cohesive. Very moist soil can be dried and broken with quicklime. Stabilization will be effective if at least 50 per cent of the aggregated clay is crushed to a diameter of less than 5 mm.

(b) Mixing

The mixing must be very carefully carried out in order to ensure the intimate mingling of the soil and the lime. For very plastic soil, the process should be carried out in two stages, with about one to two days between them. This gives the lime a chance to loosen the lumps. This two-stage procedure may nevertheless reduce the effect of the lime on strength. The homogeneity of the mix can be checked by observing the uniformity of its colour. No trail of lime not incorporated in the soil should be visible.

(c) Hold-back time

If the moist method is used, it is advantageous to allow the mixture to rest after mixing. A period of at least 2 hours should be allowed for quantities of lime above the fixing point; a period of 8 to 16 hours is preferable. The effect on dry density is negligible, but greater strengths can be achieved.

If the plastic approach is used, everything is to be gained by allowing the mixture of soil and quicklime or slaked lime to rest for several weeks. This is particularly the case for renderings which become greasier and more adhesive.

(d) Compression

Dry density is very sensitive to the degree of compaction, especially for high proportions of lime. The moisture content will be close to the optimum, on the moist side, when an adequate hold-back time has been allowed (longer for higher quantities). The exothermic reaction set off by the quicklime consumes close to 1 per cent of the moisture content per percantage of quicklime added. The moisture content will thus be corrected as OMC is approached during the second mixing stage.

(e) Drying cure

An increase in compressive strength can be obtained if the curing period is extended. This phenomenon lasts several weeks and persists for months. It is even better in a warm, humid environment. Lime-stabilized products can be very advantageously exposed to high temperatures (± 60°). Curing in the sun under a sheet of plastic or in a tunnel built of corrugated iron makes it possible to achieve such high temperatures and relative humidities. Research carried out at the University of Denmark has shown that very good products can be obtained by drying for 24 hours in an autoclave at 60-97°C with an RH of 100 per cent.

D. Bitumen

If it is to be used, the bitumen must be either heated; or mixed with solvents resulting in "cut-back"; or dispersed in water as an emulsion. It is the two latter techniques which are used for stabilization.

Cut-back and bituminous emulsions come in the form of microscopic droplets in suspension in a solvent or in water. The stabilizer is mixed in the soil, and when the water or solvent evaporates the droplets of bitumen spread out to form very thin strong films which adhere to and cover the soil. Bitumen improves the water-resisting properties of the soil (less absorption by clays) and can improve the cohesion of soils with non-cohesive soils, by acting as binder.

1. Effectiveness and proportions

In order to obtain uniform distribution of the bitumen throughout the soil, it is better to use a technique making use of large quantities of water. The adobe technique is thus the most suitable. Normally 2 to 3 per cent bitumen is added, but this can rise to 8 per cent. Proportions vary in accordance with the grain size distribution of the soil because bitumen stabilization involves the coating of the specific surface of the grains. The values given here are for the bitumen prior to being diluted in a watery suspension or by a solvent. The bitumen has only a very slight effect on the colour of the material and has no typical odour once the stabilized products have dried.

- Soil: Bitumen stabilization is most effective with sandy or silty soils. It is not suitable for fine soils in dry regions, where the pH and salt content of the soil may be high.

- Organic matter and sulphates: Their presence in the soil hinders the efficiency of bitumen stabilization, as their adhesion to the grains prevents the adhesion of bitumen. Acid organic matter (e.g., forest soils) are very harmful. The neutral and basic organic matters found in arid and semi-arid regions are not particularly harmful.

- Salts: Mineral salts are very harmful. They can be neutralized by adding 1 per cent of cement. When bitumen stabilization is carried out on an industrial scale, salt contents of more than 0.2 per cent are not accepted, but sometimes up 6 per cent of sodium chloride can be accepted.

2. Types of bitumen

When bitumen is used for stabilization it is generally in the form of cut-back or emulsion. Both forms break down on drying, and this break-down can be slow or fast. Rapid break-down is suitable for temperate climates and slow break-down is better for hot climates.

(a) Cut-backs

These are bitumens to which a volatile solvent has been added, making them less viscous. Solvents can be gas-oil, kerosene, and naphtha. Some of them dry slowly, some moderately quickly, while others dry rapidly. They cannot be used in the rain and are flammable. Their viscosity is indicated by an index number: 0 = very fluid, 3 = viscous. RC 250 is a cut-back which is widely used in the United States.

(b) Emulsions

Bitumen (55 to 65 per cent) is dispersed in water with the help of an emulsifying agent (1 to 2 per cent). This agent also keeps the bitumen in suspension.

There are two sorts of emulsion.

- Anionic: unusual and not suitable for all aggregates; used mostly in Europe;

- Cationic: more widespread and compatible with virtually all soils, used in particular in the United States.

Emulsions are usually very fluid and mix easily with soil which is already moist. They are less stable than cut-backs, and there is a danger of the water and bitumen bond breaking down (separation).

3. Production procedure

(a) Mixing

The effectiveness of bitumen stabilization depends very largely on this operation. Too much mixing can increase water absorption after drying because of the premature break-down of the emulsion. If the mixing is carried out in the liquid or plastic state (adobe, cob, mortar, or rendering), no problems of this sort are encountered.

However, if the soil is going to be compacted, the mixing should be carried out at OMC. When soils are already moist, care must be taken not to add excessive quantities of stabilizer (water and bitumen). Wet strength and impermeability may be reduced.

When low proportions of bitumen are used (e.g., 2 per cent), it is preferable to add the bitumen to a small quantity of soil, and then to mix this small quantity with the remainder of the soil. This applies particularly to cut-back. Emulsions should be diluted in the mixing water.

(b) Hold-back time

When bituminous stabilizers with slow or moderately quick break-down time are used, it is possible to wait between mixing and moulding. When products with rapid break-down times are used, operations should follow one another without delay.

(c) Compaction

20 to 40 daN/cm^2 is enough and leaves the material a fairly porous structure in order to facilitate the evaporation of volatile solvents while ensuring good dry density. When turning out from the moulds the bitumen acts as a release product. The blocks have an attractive appearance with sharp arrisses.

(d) Curing

Cut-back and emulsion which break down rapidly shorten drying times. It is preferable to allow bitumen-stabilized material to cure in dry air rather than in a moist environment. Compressive strengths are related to the quantity of bitumen used and the duration of the drying period. These two parameters should be determined in advance by means of tests to find out what the optimum values are. The loss of volatiles is greater for longer curing periods and higher temperatures, and this has a beneficial effect on absorption and expansion. Above 40°C, however, no further improvement is noted.

E. Resins

A great deal of recent research work has been concentrated on chemical stabilization by means of chemical resins, particularly in the civil engineering field. The object of this research has been to achieve an increase in load-bearing capacity while at the same time reducing the weight of stabilized earth courses. The highest shear strength combined with the greater elasticity of the wearing courses has been sought. These objectives, which correspond to civil engineering requirements, are not necessarily applicable to the construction of buildings, except for such horizontal surfaces as footways or stabilized slabs. Quite extraordinary results have been obtained with resin stabilization. The considerable extra cost compared with ordinary stabilization procedures, however, remains the greatest barrier to its widespread use.

Vigorous action, rapid setting, and easy incorporation into the soil as viscosity is comparable to that of water. Very moist soils can be solidified.

Their high cost and sophisticated production technology, only make them available in industrialized countries. The quantities required are large compared to conventional stabilizers. The products are toxic, difficult to handle, requiring the use of catalysts, sensitive to water, and their service life is uncertain as the products are biodegradable.

These resins are made up of long chain molecules resulting from the linking (polymerization) or certain chemical agents (monomers and polymers). They can be used in two different ways:

(a) Monomers are added to the soil at the same time as the catalyst: reaction between the soil and the monomers is immediate as is polymerization. This is the case of abietic resins, for example.

(b) A polymer is formed in advance by synthetic or natural means and then added to the soil as a solid, solution, or emulsion.

The resins act in different ways, as flocculants; as dispersants or as acids. The majority act to render the soil impermeable, while the more sophisticated can improve the cohesion of the soil.

The following are some popular types of resins.

(a) Gum Arabic is obtained from the acacia tree. Its impermeability is low because it is soluble in water. It acts primarily as a flocculant, helps to increase dry compression strength, and slows capillary absorption of water by acting on the kinetics of this phenomenon.

(b) Palmo-copal Copal is a resin obtained from certain tropical trees. Palmo-copal is a solution of copal obtained by pyrogenation from palm oil. The amount required varies from 3 to 8 per cent for sandy soils. Another variety, manila copal, is the only copal resin which has an impermeable capacity.

(c) Wallaba resin is a water repellent.

(d) Colophane is obtained during the distillation of turpentine essences from oily pine resins. It is soluble in organic solvents and in aqueous alkaline solutions. Colophane resin forms a gel after reacting with certain metallic salts (iron and aluminium). It reduces the water absorption of soils.

(e) Vinsol is also obtained in the production of turpentine. It is used in acid soils at critical control rates (± 1 per cent). Water repellent improves cohesion but does not affect compressive strength.

(f) Lignin is a by-productof the paper industry. It is a sort of alkaline resinous liquor with an impermeable capacity. It is soluble but can become insoluble when reacted with chrome. Chromo-lignin is, unfortunately, an expensive product.

(g) Molasses: Sugar aldehydes from dehydrated molasses can be polymerized at high temperatures with phenolic catalysts. The resinous material obtained has characteristics similar to those of a naturally occuring asphalt and synthetic resins.

(h) Ethyl cellulose: This is a synthetic resin which has been tested but without satisfactory results.

(i) Carboxymethyl cellulose: This is a non-ionic stabilizer with a coagulating action and is water soluble.

(j) Shellac confers excellent strength on sandy soils but the stabilized material does not stand up well to water.

F. Natural products

1. Mineral products

These products are used to correct the grain size distribution of soils. For example, sands can be added to clays and vice versa. Sometimes very specific soils are selected in order to obtain very particular effects. A good example is bentonite, which is added in small quantities to the soil being treated. This smectic clay has powerful degreasing properties and expands in the presence of water, thus preventing the passage of water.

Some soils (volcanic sands in particular) have natural pozzolanic properties. They can be used for stabilizing clayey soils but often require the addition of at least 30 per cent of lime or cement before becoming an effective binder which in turn will stabilize clay when added at a rate of about 8 per cent.

2. Animal products

These are only very rarely used for stabilizing walls or solid elements of a building. They tend to be reserved for the stabilization of renderings.

(a) Excrement: All sorts of excrement are used. Cowpats are undoubtedly the most widely employed, although they are better used as a manure or fuel. This particular excrement has in the final analysis only a very limited effect on water resistance and reduces compression strength. Other traditions make use of horse or camel dung, or of pigeon droppings. The action of these sorts of excrement is probably due to the presence of fibre (mixed straw), phosoporic acid and potassium. The use of animal urine is also known. Horse urine when used to replace the mixing water (e.g., for daub) effectively eliminates cracking and gives a marked improvement in the ability of the soil to stand up to erosion. Surprisingly good results can be obtained when it is combined with lime.

(b) Animal blood: The use of bull's blood is known from Roman times. When combined with lime or polyphenols, stabilization with bull's blood is effective. The blood must be fresh and not be in powder form.

(c) Animal fur and hair: Animal hair and fur play much the same role as some vegetable fibres. Their use is generally reserved for stabilizing renderings.

(d) Casein: Proteinic casein (middle fraction of the protides of milk) is sometimes used in stabilization in the form of whey combined with bull's blood. Certain milk powders have been tried and gave good results. "Poulh's soap" is also used. This is diluted casein. It is beaten like a paste, after first being mixed with brick dust prior to being added to the soil.

(e) Lime: Lime can be prepared from shells or coral. This is still done in some countries such as Senegal and Somalia.

(f) Animal glues: These can be used for stabilization, particularly for renderings. Animal glues are produced from horn, bone, hooves, and hides.

(g) Termite hills: Termites secrete an active substance, which appears to be a non-ionic cellulose polymer of the polysaccharide type. Termite hills stand up well to rain and their soil can be mixed with another for the production of blocks. The substance has been synthesized by research workers in South Africa, but costs three times as much as cement.

(h) Oils and fats: Fish oils and animal fats can serve as waterproofing agents. Similarly the stearates contained in animal fats play the same role.

3. Vegetable products

(a) Ashes: Hardwood ash is rich in calcium carbonate and has stabilizing properties but is not always suitable for soils which may be suited to lime stabilization. Classic proportions suggest the addition of 5 to 10 per cent ash. Ashes improve the dry compression strength but do not reduce sensitivity to water.

(b) Vegetable oils and fats: If they are to be effective, vegetable oils must dry quickly so that they harden upon contact with the air and are insoluble in water. The use of castor oil is highly effective, but it is extremely expensive. Coconut, cotton, and linseed oils are also used. Kapok oil prepared first by roasting kapok seeds, turning them into a flour which can then be transformed into a paste (20 to 25 l of water to 10 kg of powder) can be effective. This depends on the quality of the seeds and the roasting process, which increases the yield, as well as the length of time it takes to prepare the paste (6 hours boiling). Palmitic acid is obtained from saponified palm oil precipitated by 25 per cent HCl. About 1 kg of palmitic acid is obtained per kg of palm soap in solution.

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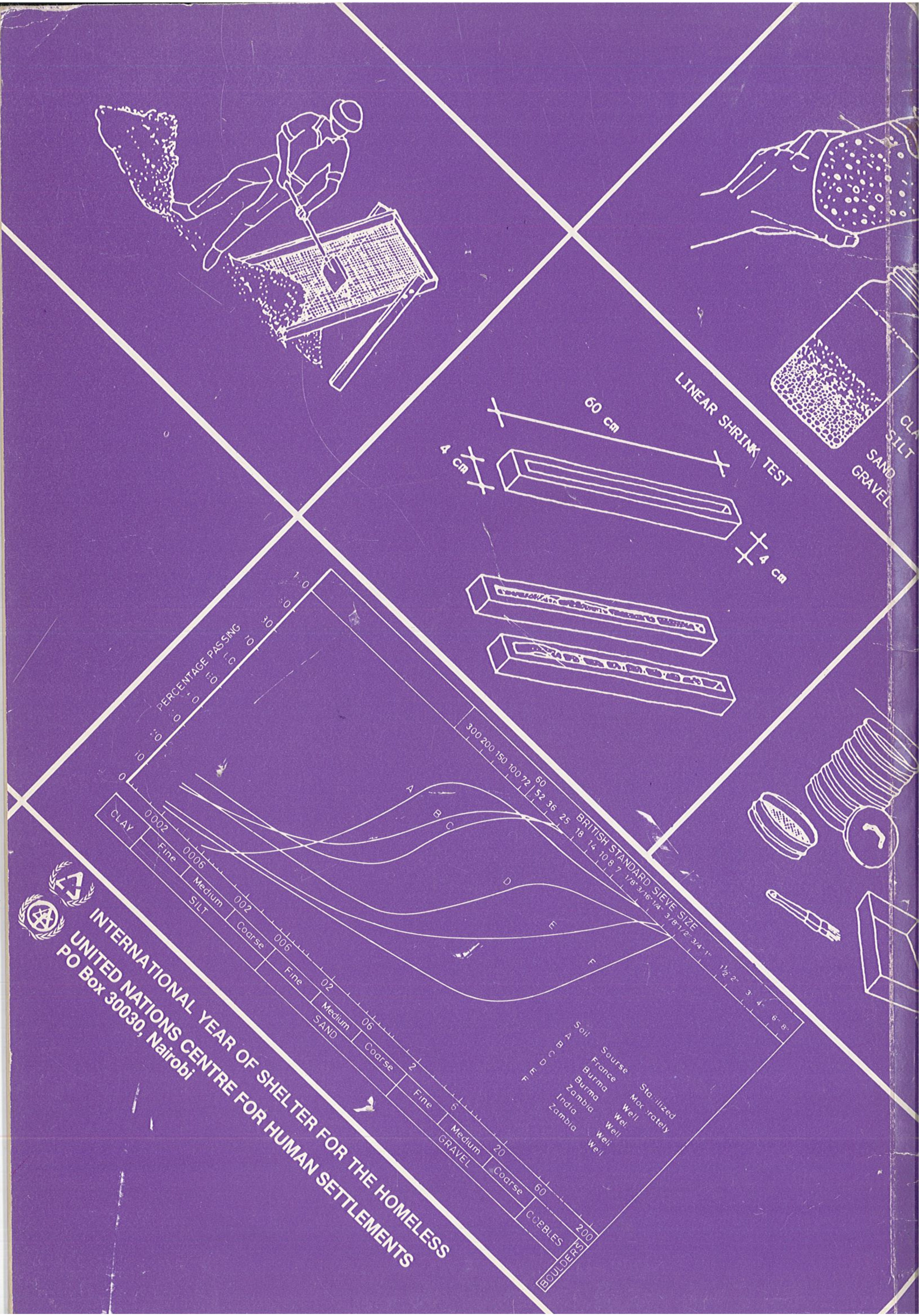

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